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by William R. Wade and Donald J. Progar

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SUMMARY

This paper presents the design, the uncertainty analysis, and the test results for several selected materials of a transient calorimetric apparatus for measurement of the total hemispherical emittance of materials for a temperature range from 223° K to 523° K.

The uncertainties of the system define the type and magnitude of systematic errors when the calorimetric method of measuring emittance is utilized. The design details which minimize or eliminate these errors are emphasized in the description of the system design. Maximum probable uncertainty has been determined for this system and the results of test runs on highly polished samples of copper and aluminum compare favorably with values of total emittance published by other investigators.

INTRODUCTION

Since thermal radiation is the primary method of heat transfer between a space vehicle and its environment, calculations for a passive thermal control design require that the radiative properties of spacecraft surfaces be accurately known for temperatures ranging from near 200° K to as high as 400° K. Much of this information as available in existing technical literature is not generally applicable because of variations in sample preparation or surface finish. As a result, the desired optical properties of a material are best obtained from test samples prepared in the same manner as the spacecraft surfaces.

Methods commonly used to determine the total emittance of materials include the radiometric, reflectance, and calorimetric techniques. However, the first two methods mentioned are subject to serious errors over the relatively low-temperature range encountered by actual spacecraft surfaces. Radiometric techniques, for example, are subject to problems of detection of low levels of radiation intensity. This detection requires measurement of emittance at higher temperatures with an extrapolation of the

data to the low temperatures desired. This procedure often leaves the values obtained open to question.

Total emittance values as determined from measured values of spectral reflectance by Kirchhoff's law are subject to gross error when the measured values of reflectance are very high.

In view of the limitations of the radiometric method and the gross error possible in the reflectance method, the method that is generally considered the most accurate means of determining the total hemispherical emittance of materials at low temperatures is the calorimetric method. This technique consists of positioning a test sample within an evacuated enclosure with walls that are blackened and maintained at a temperature much lower than that of the test sample. This method, as it is commonly employed, requires that an electric heater be embedded in the test sample with possible large and unaccountable errors resulting because of the conductive heat transfer to or from the test sample by the heater lead wires. This source of error is eliminated with the apparatus described in this paper which is unique in that a radio-frequency induction heater is used to heat the test sample by placing the load coil of the induction heater inside the vacuum chamber. This departure from the conventional internal sample heater also simplifies the fabrication of test samples.

This paper presents the design details, and a detailed analysis of possible errors to be encountered for a transient calorimetric apparatus for measuring total hemispherical emittance over a temperature range from 223° K to 523° K (or higher). Measured values of total emittance are presented for highly polished samples of aluminum, copper, and stainless steel.

SYMBOLS

A	cross-sectional area, centimeters^2
c_p	specific heat of test sample, joules/kilogram-°Kelvin
E	electromotive force, volts
I	current, amperes
k	thermal conductivity, joules/centimeter-second-°Kelvin

l	length, centimeters
M	molecular weight
m	mass, kilograms
P	perimeter, centimeters
p	pressure, newtons/meter^2
q	rate of energy loss, joules/second
R	radius, centimeters
S	surface area, centimeters^2
T	temperature, ^{o}Kelvin
$\dot{T}$	time derivative of sample temperature, ^{o}Kelvin/second
t	time, seconds
α	absorptance (also, accommodation coefficient in Knudsen's eq. (23))
γ	ratio of specific heats
Δ	difference between two measured quantities
δ	difference between actual and measured quantity
ϵ	emittance
ρ	reflectance

σ	Stefan-Boltzmann constant, 5.675×10^{-12} joule/second-centimeter^2-^{o}Kelvin
$\frac{\delta\epsilon_s}{\epsilon_s}$	error in emittance, percent

Subscripts:

Al	alumel wire
a	ambient
C	conventional error
Ch	chromel wire
g	residual gases
gage	vacuum gage
H	heat measurement error
L	error due to heat losses in system
max	maximum
min	minimum
o	enclosure wall
s	sample
w	lead wires

CALORIMETRIC TECHNIQUES

The general heat balance equation for a body at a temperature T_S with an emittance of ϵ_S suspended in a calorimetric enclosure with wall temperature of T_O and an emittance of ϵ_O can be expressed as (ref. 1):

$$q_S = \sigma\epsilon_S S_S T_S^4 - \sigma\alpha_S S_S T_O^4 - \sigma\alpha_S\epsilon_S\rho_O \frac{S_S^2}{S_O} T_S^4 + q_L \tag{1}$$

where q_S is the rate of energy loss by the sample which must be equal to the rate of energy loss by radiation from the sample surface plus any losses due to thermal conduction by sample supports or residual gases in the enclosure. The terms on the right include: (1) the energy radiated by the sample surface, (2) the energy radiated by the enclosure walls and absorbed by the sample surface, (3) the energy radiated by the sample surface, reflected by the enclosure walls, and absorbed by the sample, and (4) the term q_L which represents losses due to conductive heat transfer. By rewriting expression (1) as

$$q_S - q_L = \sigma\epsilon_S S_S T_S^4 \left(1 - \alpha_S\rho_O \frac{S_S}{S_O}\right) - \sigma\alpha_S S_S T_O^4 \tag{2}$$

it can be seen that for small values of the ratio $\frac{S_S}{S_O}$ the reflectance term $\alpha_S\rho_O \frac{S_S}{S_O}$ becomes small when compared with unity and can thus be neglected.

In addition, as T_S approaches T_O, the absorptance of the sample for radiation from the chamber walls becomes approximately equal to the sample emittance. For a T_S much greater than T_O, the emission of radiant energy by the enclosure walls becomes negligible with respect to that of the sample emitted energy. Therefore, it may be assumed that $\epsilon_S = \alpha_S$ and equation (2) may be written as

$$q_S - q_L = \sigma\epsilon_S S_S \left(T_S^4 - T_O^4\right) \tag{3}$$

The total emittance of the test sample can then be determined from

$$\epsilon_S = \frac{q_S - q_L}{\sigma S_S \left(T_S^4 - T_O^4\right)} \tag{4}$$

The total hemispherical emittance of a test surface may be determined from equation (4) by using either a "steady-state" or a "transient" technique. In the steady-state technique the test sample is maintained at a specified temperature by means of a known

power input (from an internal sample heater) and emittance is calculated from expression (4), where $q_S = EI$, as

$$\epsilon_S = \frac{EI - q_L}{S_S\sigma\left(T_S^4 - T_O^4\right)} \tag{5}$$

The transient technique, used in this investigation, utilizes the measured temperature time history of the test sample while cooling by radiation to the enclosure walls, and knowledge of certain physical properties of the test sample to obtain emittance from equation (4) where $q_S = mc_p\dot{T}$:

$$\epsilon_S = \frac{mc_p\dot{T} - q_L}{S_S\sigma\left(T_S^4 - T_O^4\right)} \tag{6}$$

SYSTEM DESIGN

The calorimetric method can be an accurate method for obtaining total emittance values at low temperatures; however, there are several possible sources of error inherent in this method. To insure that the measured values of emittance are not subject to gross error, considerable care must be exercised in the design of the apparatus and in the test procedures.

The main systematic errors that can be encountered in the calorimetric measurement of emittance are due to heat conduction by sample support wires and thermocouple lead wires and by residual gas conduction in the vacuum chamber. In addition, errors in emittance can result from errors in sample temperature measurement, errors in the measurement of the temperature-time response of the sample, and errors in the measurement of certain properties of the test sample such as mass, area, and specific heat. In the description of the test apparatus and techniques which follows, the design features and test techniques intended to eliminate or minimize the main systematic errors are emphasized.

Test Sample

Configuration of the test sample depends primarily on two considerations: first, that no area of the sample "see" any other sample area; and secondly, that the sample surface area be small in comparison with the surface area of the surrounding enclosure. With these considerations in mind, the sample configuration is then simply a matter of individual preference. In this investigation the test samples were fabricated as right circular cylinders with a diameter of 1.27 centimeters and a length of 1.27 centimeters.

Test Enclosure

The design of an apparatus for measurement of total hemispherical emittance by the calorimetric method must minimize the errors associated with reflection by the enclosure walls of sample emitted energy and by the radiation of energy from the enclosure walls. This minimization of errors is accomplished by making the ratio of wall area to sample area as large as practical, by coating the enclosure walls with a highly absorbing surface, and by maintaining the enclosure walls at a temperature much lower than the minimum test sample temperature.

The test enclosure, shown in figures 1 and 2, was fabricated as a stainless-steel sphere 20.32 centimeters in diameter. This sphere provides for a ratio of enclosure surface area to test sample surface area greater than 170. A flat black paint (Pyromark black) with a measured absorptance of 0.90 or greater over the wavelength range from 1 to 26 micrometers was used to coat all interior surfaces of the sphere to provide a highly absorbing surface. This paint was used to limit the outgassing rate from the enclosure walls during pump down of the system and prior to cooling of the walls. During tests, the sphere was completely immersed in liquid nitrogen contained in the wide-mouth Dewar container shown in figure 3 to maintain the temperature of the enclosure walls at 77.6° K.

To minimize the effects of gaseous conduction (and convection) on measured values of emittance, the system pressure was reduced to 1.33×10^{-4} newton/meter^2 and maintained at this pressure during tests by use of a 50 liter/second ionization pump shown in figure 3.

Test samples were heated to the desired test temperature by use of a 500-watt radio-frequency induction heater with the load coil placed in the pumping duct of the vacuum system as shown in figures 1 and 2. The test sample, suspended by thermocouple leads, was transferred from the center of the induction coil to the test sphere by use of a magnetically coupled, high-vacuum, push-pull feedthrough mounted on the vacuum system as shown in figures 1 and 2. This method of heating the test sample eliminates the uncertainties encountered when an internal sample heater is used because of the unknown specific heat of the heating element and the thermal conductance of the necessary power leads.

To eliminate radiant heat transfer between the test sample and the pumping duct of the system, a spherical segment of blackened copper was used as a shield at the juncture of the test sphere and pumping duct. This shield was held in place by spring clips which serve as conductive links to the sphere walls and thus the shield was maintained near the temperature of the liquid nitrogen.

Instrumentation

Accurate emittance measurements by the transient calorimetric technique require that an accurate temperature time history of the test sample be obtained. To insure accuracy of these measurements, all thermocouples used in this investigation were calibrated prior to use and were found to be accurate to within $\pm 0.5^{\circ}$ K over the temperature range of the tests. Conductive heat loss by the sample due to thermocouple conductance was minimized by use of 36-gage AWG chromel-alumel leads (which also serve as sample support wires). The temperature time history of the test sample was recorded by the millivolt recording potentiometer shown in figure 3, which was calibrated prior to and after each test by use of the manually balanced precision potentiometer also shown in figure 3. The system instrumentation also included a thermocouple gage and an ionization gage for monitoring system pressure. The overall view of the test apparatus is shown in figure 3.

Uncertainty Analysis

If it is assumed that the major uncertainties encountered in the calorimetric measurement of total emittance are systematic rather than random, they will add in a linear manner and the total uncertainty can be expressed as

$$\frac{\delta\epsilon_S}{\epsilon_S} = \left(\frac{\delta\epsilon_S}{\epsilon_S}\right)_C + \left(\frac{\delta\epsilon_S}{\epsilon_S}\right)_H + \left(\frac{\delta\epsilon_S}{\epsilon_S}\right)_L \tag{7}$$

where the terms on the right are defined as the "conventional error," the "heat-measurement error" and the error due to "heat losses," respectively. These uncertainties are discussed in the following paragraphs.

Conventional Error

The conventional error contribution to the total uncertainty involves error in measurement of the basic physical quantities of an emittance sample such as the area of the sample, the temperature of the sample, and the enclosure temperature. This error can be expressed as

$$\left(\frac{\delta\epsilon_S}{\epsilon_S}\right)_C = \frac{\delta S_S}{S_S} + 4\left(\frac{T_S^4}{T_S^4 - T_O^4}\right)\frac{\delta T_S}{T_S} + 4\left(\frac{T_O^4}{T_S^4 - T_O^4}\right)\frac{\delta T_O}{T_O} \tag{8}$$

In a given system, each of the quantities in equation (8) is subject to varying degrees of accuracy; however, the most significant uncertainty occurs in measurement of sample temperature. The magnitude of the uncertainties of sample and enclosure temperatures

can be determined when thermocouples with known accuracies are utilized (that is, calibrated). Thermocouples used in this investigation were calibrated prior to use and were found to have a maximum deviation of $\pm 0.5^{\circ}$ K. The maximum uncertainty in emittance due to this temperature measurement uncertainty will occur at the minimum test temperature of 223° K. From expression (8), the uncertainty due to sample temperature measurement is ±0.909 percent and that due to uncertainty of enclosure temperature is ±0.038 percent; thus a total uncertainty of calculated emittance values of ±0.947 percent results.

The uncertainty in sample area was determined from the uncertainty involved in measurement of sample dimensions when conventional micrometers are used. Each dimension can be in error by 2.54×10^{-5} meter which results in an uncertainty of sample area of 2.50×10^{-6} meter^2 or as uncertainty in the calculated values of emittance of ±0.33 percent.

Heat-Measurement Error

The error in determination of heat radiated by the test sample to the enclosure walls includes the uncertainties in measurement of $\dot{T}$, sample mass, and specific heat of the test sample which can be expressed as

$$\left(\frac{\delta \epsilon_s}{\epsilon_s}\right)_H = \frac{\delta m}{m} + \frac{\delta c_p}{c_p} + \frac{\delta \dot{T}}{\dot{T}} \tag{9}$$

The uncertainty in determination of sample mass was the manufacturer's stated uncertainty of $\pm 0.1 \times 10^{-6}$ kg for the precision balance used to determine sample mass. This δm resulted in an uncertainty of calculated sample emittance of ±0.0025 percent for the aluminum (1100) sample, and ±0.0007 percent for the copper (OFHC) and stainless-steel (347) samples.

The uncertainties of specific-heat values as published in the technical literature (refs. 2 and 3) are dependent on the sample material; stated values of c_p are known to a higher degree of accuracy for elemental materials than for alloys. The published values of c_p for the commercially pure aluminum (99^+ percent) and copper (99.95^+ percent) used in this investigation are known to within ±1 percent. The values of c_p for the stainless-steel alloy are claimed to be accurate to ±5 percent. These uncertainties in c_p are considered as maximum and result in like uncertainties in values of calculated values of emittance. For emittance measurements of coating materials with an unknown c_p, an elemental substrate material should be used. This procedure will minimize the uncertainty of the coating c_p if the coating is maintained at a small fraction of the total sample mass.

For the system described in this paper, the uncertainty in measurement of $\dot{T}$ results from the uncertainties of sample temperature measurement ($\pm 0.5^{o}$ K) and measurement of time intervals (± 0.3 second). The maximum uncertainty in $\dot{T}$ was determined from the experimentally measured time interval Δt for a sample temperature change ΔT of 25^{o} K when the slope of the cooling curve is greatest (that is, the shortest time interval Δt for the 25^{o} K ΔT) from the expression:

$$\dot{T} = \frac{\Delta T}{\Delta t} \tag{10}$$

then

$$\delta\dot{T} = \frac{\Delta t\ \delta T - \Delta T\ \delta t}{\Delta t^2} \tag{11}$$

Using the values of $\delta\dot{T}_{max}$ obtained by this expression resulted in an uncertainty in calculated values of emittance of approximately 4.0 percent for all test samples.

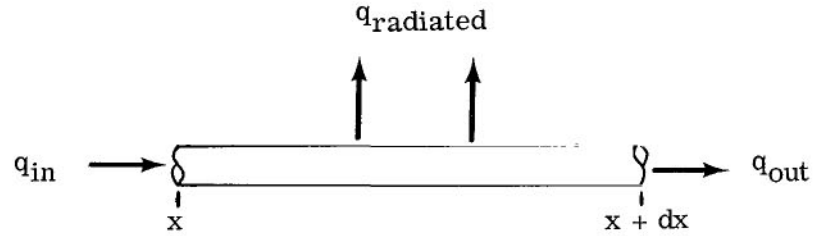
Heat Losses

The error in measured emittance values due to conductive heat loss by the sample through lead wires or residual gases in the test chamber can be expressed as

$$\left(\frac{\delta\epsilon_s}{\epsilon_s}\right)_C = \left[\frac{1}{\epsilon_s S_s \sigma\left(T_s^4 - T_o^4\right)}\right]\left(q_w + q_g\right) \tag{12}$$

where q_w represents the heat loss by lead-wire thermal conductance and radiation. The effect of this heat loss on the values of sample emittance was determined by the following analysis.

Consider a wire of infinite length with a heat source T_s at $x = 0$ and T_a at $x = l$. (See sketch (a).) Heat is being conducted along the wire (no radial heat transfer)



Sketch (a)

and there is no reradiation to the wire from the enclosure walls. For a differential length of this wire,

$$q_{in} = q_{out} + q_{radiated} \tag{13}$$

$$\left(-k_w A_w \frac{dT}{dx}\right) = \left[-k_w A_w \frac{dT}{dx} - \frac{d}{dx}\left(k_w A_w \frac{dT}{dx}\, dx\right)\right] - \sigma \epsilon_w P_w\, dx\, T_w^4 \tag{14}$$

Assume that the surface temperature of the wire is approximately T_w at x and uniform over the increment Δx. Combining and rearranging equation (14) yields

$$-k_w A_w \frac{d}{dx}\left(\frac{dT}{dx}\right) = \sigma \epsilon_w P_w T_w^4 \tag{15}$$

or

$$\frac{d}{dx}\left(\frac{dT}{dx}\right) = -\frac{2\sigma \epsilon_w}{k_w R_w} T_w^4 \tag{16}$$

Let

$$N^2 = -\frac{2\sigma \epsilon_w}{k_w R_w} \tag{17}$$

then

$$\frac{d}{dx}\left(\frac{dT}{dx}\right) = N^2 T_w^4 \tag{18}$$

Multiplying $\frac{d}{dx}\frac{dT}{dx}$ by $\frac{dT}{dT}$ yields

$$\frac{d}{dT}\left[\left(\frac{dT}{dx}\right)^2\right] = N^2 T_w^4 \tag{19}$$

Integration of equation (19) and evaluating at $T_{x=0}$ and $T_{x=\ell}$ yields

$$\left(\frac{dT}{dx}\right)^3 \Bigg|_{\left(\frac{dT}{dx}\right)_{x=0}}^{\left(\frac{dT}{dx}\right)_{x=\ell}} = \frac{3N^2 T_w^5}{5} \Bigg|_{T_{x=0}}^{T_{x=\ell}} \tag{20}$$

For an infinite length of wire, $\frac{dT}{dx} = 0$ at $x = \ell$; thus,

$$\left.\frac{dT}{dx}\right|_{x=0} = \left[\frac{3}{5} N^2 \left(T_s^5 - T_a^5\right)\right]^{1/3} \tag{21}$$

The heat loss due to the wire can then be determined by

$$q_w = k_w' A_w \left(\frac{dT}{dx}\right)_{x=0} \tag{22}$$

where $k_w' = k_{Al} + k_{Ch}$. (See ref. 4.)

This calculation was performed for $T_s = 500^\circ$ K and $T_a = 300^\circ$ K, and the heat loss due to thermocouple wire conduction and radiation was 1.94 joules/sec. This heat loss results in uncertainty of emittance of 2.06 percent for the aluminum sample, 2.57 percent for the copper sample, and 0.48 percent for the stainless-steel sample.

The errors in emittance values as measured by calorimetric methods can become very large unless the test chamber is maintained at low pressures to minimize heat losses from the test sample due to conduction by residual gases. An estimate of the heat loss that may be experienced as a result of this gaseous conduction is made by use of the relation developed by Knudsen (ref. 5) for heat transfer between long coaxial cylinders. Since the ratio S_s/S_o for the system described here is small (0.006), the assumption of concentric geometry can be considered valid and, therefore,

$$q_g = 2.426 \times 10^{-4} S_s \frac{\alpha_o \alpha_s}{\alpha_o + \frac{S_s}{S_o}(1 - \alpha_o)\alpha_s} \frac{\gamma + 1}{\gamma - 1} \frac{p}{\sqrt{MT_{gage}}} (T_s - T_o) \tag{23}$$

The accommodation coefficients are assumed to be unity and the pressure was measured at a gage temperature of 300° K. In this investigation, the maximum pressure during test was 1.33×10^{-4} newton/meter^2, and the minimum test temperature was 223° K. The maximum error in measured values of emittance due to gaseous conduction losses for these test conditions was determined to be 0.8 percent for aluminum, 0.7 percent for copper, and 0.02 percent for stainless steel.

Nongray Surface Error

In addition to the systematic errors discussed, there are other possible sources of error inherent in the calorimetric method due to the effect of nonblack enclosure walls and the nongray surfaces of test samples. These errors were discussed in the section "Calorimetric Techniques." For the system described here, the ratio $\frac{S_s}{S_o} = 0.006$ and $\epsilon_o = 0.90$; thus, the reflectance term of equation (2) $\alpha_s \rho_o \frac{S_s}{S_o}$ can be considered to be negligible since it cannot exceed 6×10^{-4}.

Random Error

Inaccuracies in the experimental measurement of total emittance by the apparatus described here can be of two types, systematic or random. The sources and magnitudes of the systematic error have been discussed in the preceding paragraphs. The magnitude of the random error may be assessed from the degree of repeatability of measurement performed on identical test samples under identical test conditions.

The results of five calibration tests on a highly polished stainless-steel test sample as shown in figure 4(a) indicate the scatter which may be attributed to random error. This plot shows a maximum scatter for all five test runs of 0.006 emittance units and a maximum deviation from the average values of the five runs of ±0.003 emittance units. Table I indicates the source of possible uncertainties in measured values of emittance encountered in the system described in this paper, the maximum magnitude of these uncertainties, and the effect on the resulting emittance values.

All the errors shown do not affect the calculated emittance values in the same manner. For example, the uncertainties of measurements of the various physical properties and temperatures of the sample can be either a positive or negative value, whereas the uncertainties due to thermal conduction by support wires and residual gases will be only positive, and that due to nonblack walls or to a nongray sample will be only negative.

TEST RESULTS

Measurements of the total hemispherical emittance were made by using the apparatus described in this paper for aluminum, copper, and stainless steel to determine the accuracy and repeatability of the results. These sample materials were not selected with regard to their importance as spacecraft construction materials, but primarily as easily available materials with a range of physical properties and thermal radiation characteristics.

The samples of copper and aluminum were electropolished and the stainless-steel samples were mechanically polished to a mirror finish (1.5 microinch (0.38 nm)). The measured emittance values for these samples are shown in figure 4 for two or more identical samples of each material. The measured values of emittance for the stainless steel shown in figure 4(a) ranged from 0.109 at 235° K to 0.153 at 510° K. The repeatability of the measurements was within the ±0.003 emittance units as mentioned previously. No comparable data were found for the stainless steel.

Measured values of total emittance for the polished aluminum samples shown in figure 4(b) ranged from 0.026 at 238° K to 0.037 at 510° K. The repeatability of these measurements was well within the ±0.003 emittance units attributed to random scatter and

compared very favorably with values reported by another investigator (ref. 6) also shown in figure 4(b). The measured values for the polished copper samples are shown in figure 4(c) and range from 0.035 at 235° K to 0.029 at 510° K. The repeatability of these measured values was also within ±0.003 emittance units and the values show close agreement with those reported in reference 1 as shown in figure 4(c). In view of the repeatability of the measured values of total hemispherical emittance and the good agreement with values reported by other investigators (shown in figs. 4(b) and 4(c)), it is felt that the system accuracy as discussed in the error analysis section is realistic and that the accuracy of the emittance measurements is limited only by the parameters discussed here.

CONCLUDING REMARKS

The use of a radio-frequency induction heater to heat the test sample to a desired initial temperature eliminates the uncertainties in the emittance measurements associated with thermal conductance by heater lead wires and the unknown specific heat of an internal sample heater. The uncertainty analysis indicates that the maximum uncertainty of the emittance values obtained are within -6.0 percent to 9.0 percent with a precision of ±0.003 emittance units if the specific heat of the sample is known to 1.0 percent. Comparison of values of total emittance obtained by this system with those published by others for samples with similar surface treatment indicates good agreement. The results presented have established the validity of using the apparatus and techniques described for measurements of total emittance of surfaces at low temperatures.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., Dec. 13, 1968,
124-09-18-05-23.

REFERENCES

1. Gaumer, R. E.; McKellar, L. A.; Streed, E. R.; Frame, K. L.; and Grammer, J. R.: Calorimetric Determinations of Thermal Radiation Characteristics. Progress in International Research on Thermodynamic and Transport Properties, Joseph F. Masi and Donald H. Tsai, eds., Amer. Soc. Mech. Eng., c.1962, pp. 575-587.

2. Touloukian, Y. S.: Recommended Values of the Thermophysical Properties of Eight Alloys, Major Constituents and Their Oxides. NBS Subcontract No. CST-7590, NASA order R-45, Thermophys. Properties Res. Center, Purdue Univ., Feb. 1966.

3. Goldsmith, Alexander; Waterman, Thomas E.; and Hirschhorn, Harry J.: Thermophysical Properties of Solid Materials. Volume I: Elements. Rev. ed., The Macmillan Co., 1961.

4. Everhart, John L.; Lindlief, W. Earl; Kanegis, James; Weissler, Pearl G.; and Siegel, Frieda: Mechanical Properties of Metals and Alloys. NBS Circ. C447, U.S. Dep. Com., Dec. 1, 1943.

5. Scott, Russell Burton: Cryogenic Engineering. D. Van Nostrand Co., Inc., 1959.

6. Wittenberg, A. M.: The Measurement of the Total Hemispherical Emissivity of Materials Used in Telstar. Materials for Space Vehicle Use, Vol. 3, Soc. Aerosp. Mater. Process Eng., Nov. 1963.

TABLE I.- ERROR SOURCES

Source	Magnitude (maximum)	Effect on measured ϵ_s values
δS_s	$\pm 2.50 \times 10^{-6}$ meter^2	±0.33 percent
δT_s	$\pm 0.5^{\circ}$ K	±0.91 percent $\left(\text{at } (T_s)_{min}\right)$
δT_o	$\pm 0.5^{\circ}$ K	±0.04 percent $\left(\text{at } (T_s)_{min}\right)$
δm	$\pm 0.10 \times 10^{-6}$ kg	±0.0025 percent
δc_p	±1 percent (for elemental materials) ±5 percent (for alloys)	±1.0 percent ±5.0 percent
$\delta \dot{T}$	$\pm 8.5 \times 10^{-4}$ $^{\circ}$K/sec for aluminum; $\pm 4.7 \times 10^{-4}$ $^{\circ}$K/sec for copper; $\pm 2.0 \times 10^{-4}$ $^{\circ}$K/sec for stainless steel	±4.0 percent
Thermocouple lead-wire losses	$+1.94 \times 10^{-3}$ joule/sec $\left(\text{at } T_s = 500^{\circ} \text{ K}\right)$	+2.0 percent for aluminum; +2.6 percent for copper; +0.5 percent for stainless steel
Residual gas conduction losses	$+2.3 \times 10^{-6}$ joule/sec $\left(\text{at } T_s = 223^{\circ} \text{ K}\right)$	+0.8 percent for aluminum; +0.07 percent for copper; +0.02 percent for stainless steel
Nonblack enclosure walls and/or nongray test sample	-6×10^{-4} (dimensionless factor)	-0.06 percent
Random scatter (precision)	±0.003 emittance units	±11.5 percent for aluminum; ±10.3 percent for copper; ±2.8 percent for stainless steel

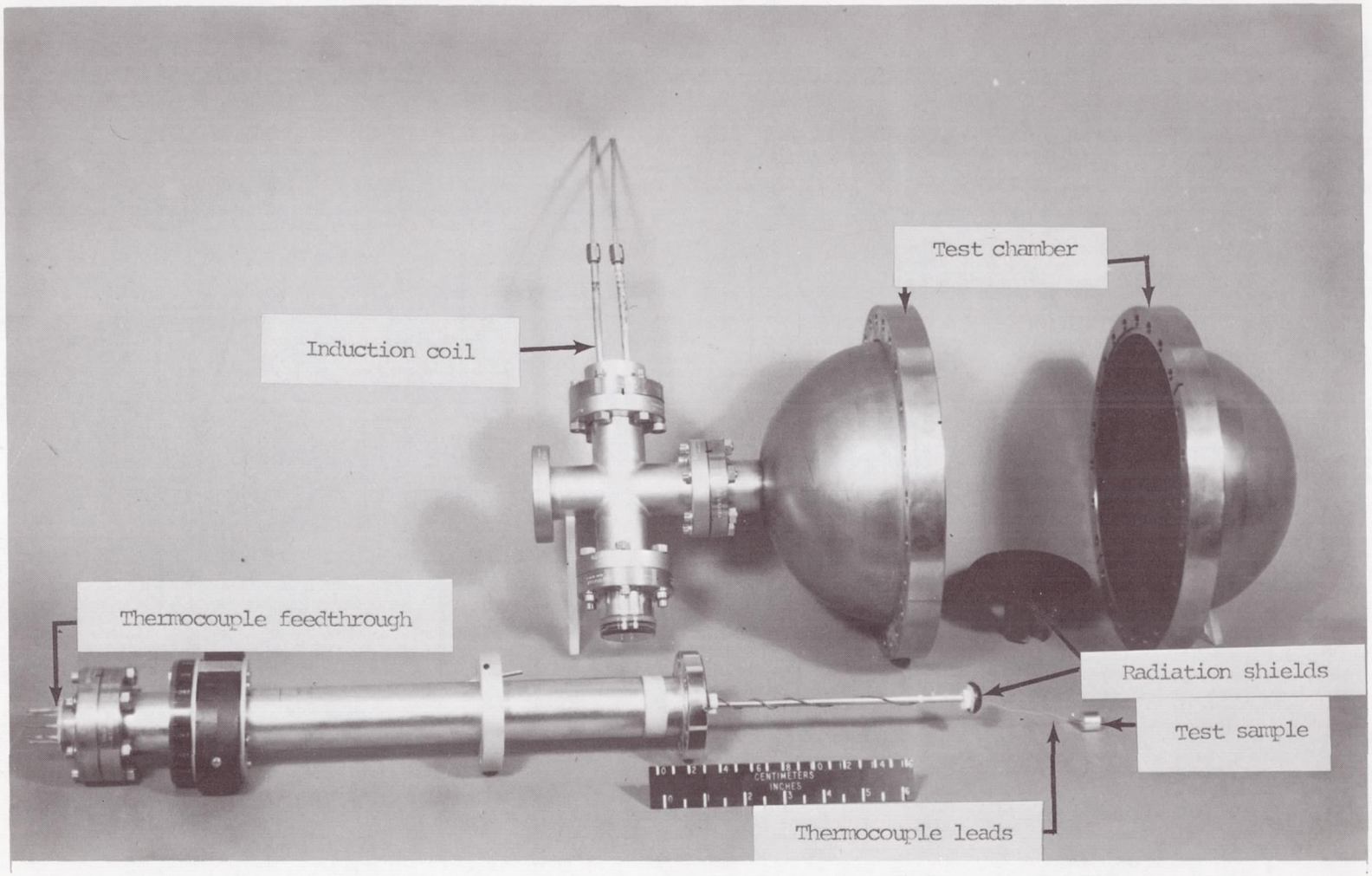


Figure 1.- Test chamber and associated apparatus for total hemispherical emittance measurements. L-67-8672.1

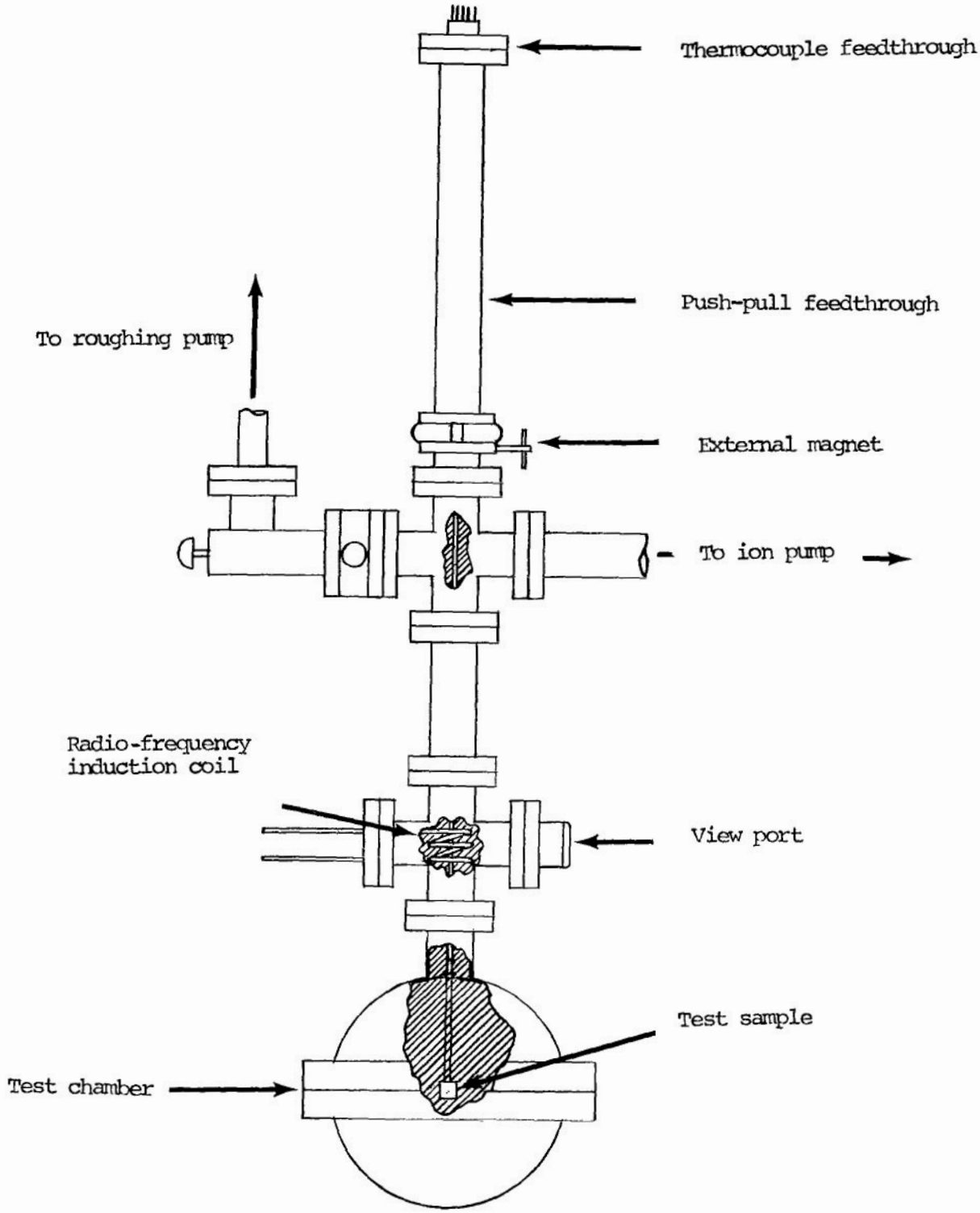


Figure 2.- Illustration showing test sample positioning and heating apparatus.

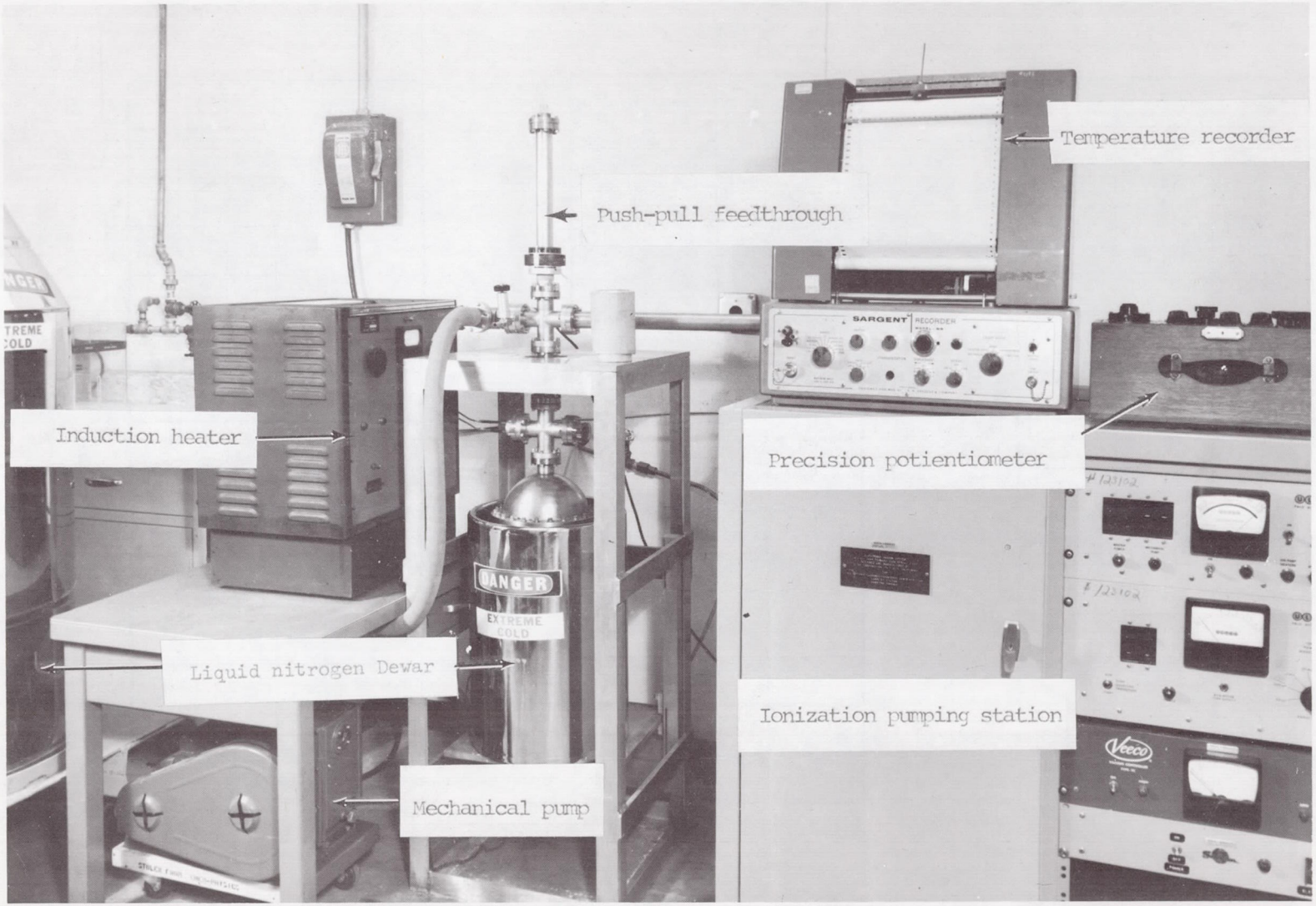
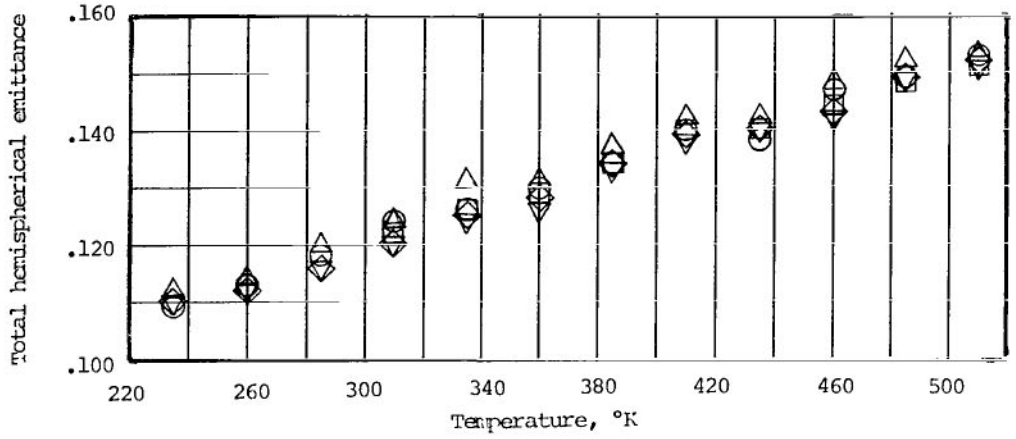
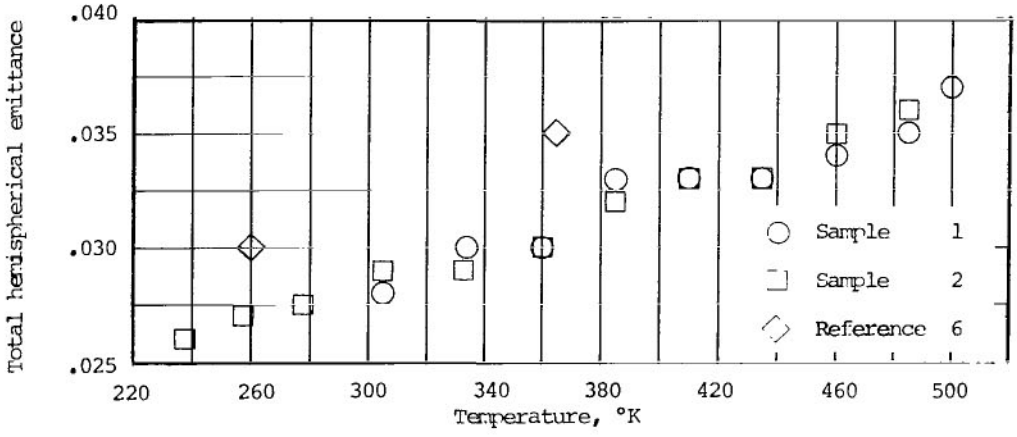


Figure 3.- Overall view of experimental apparatus.

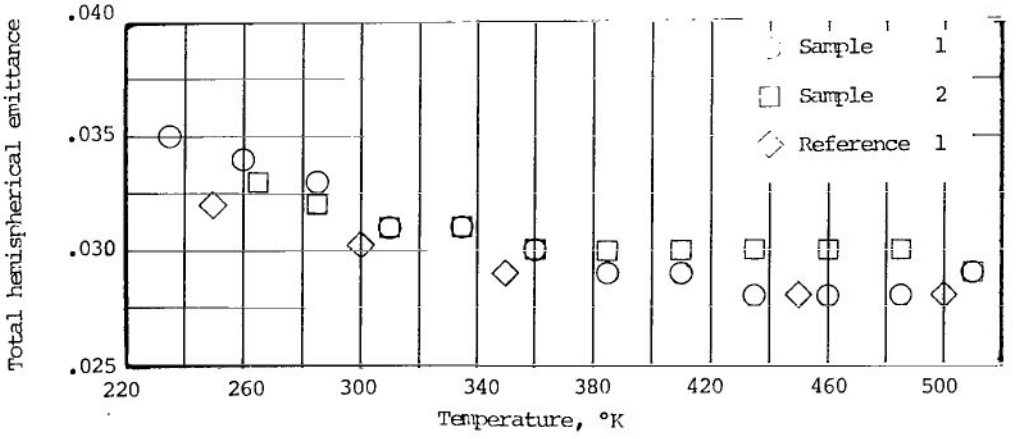
L-67-8669.1



(a) Stainless steel.



(b) Aluminum.



(c) Copper.

Figure 4.- Total hemispherical emittance as a function of sample temperature.

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